

Nordic AI Meet 2026

P4: Machine Learning, Intelligent Systems & AI for Science and Engineering

8. Carbon-Aware Adaptive Knowledge Injection for Sustainable, Trustworthy AI in Resource-Constrained Predictive Modelling

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Abstract: The use of domain-specific knowledge for improving predictive models via a process called knowledge-guided machine learning (KGML) can help increase model accuracy by incorporating aspects such as constraints, relational graphs, and expert rules; however, existing KGML methods do knowledge injection irrespective of the need for such injection based on the inputs. Many sustainable AI methods aim to make AI systems more environment-friendly by external means, e.g. choosing low-carbon grids to schedule compute resources.

Most frameworks in the literature do not make explicit efforts to assess accuracy enhancements by knowledge injection of additional inputs (versus increased carbon emissions). We propose Carbon-Aware Adaptive Knowledge Injection (CAKI), which views knowledge addition not as a fixed attribute but as a decision taken on a per-inference basis through cost-benefit criteria. This is with respect to sustainable AI for the environment, entailing societal benefits. It has three paths: a domain-constrained path encoding physical or environmental relationships as soft constraints; a graph path encoding domain-specific dependencies; and a correction rule-based path applying expert thresholds to post-hoc tune prediction results, with each entailing a measurable and traceable cost of energy and carbon emissions. There are three criteria to guide decision making: Knowledge Utility Score (KUS), representing an estimate of how much accuracy would be gained by injection per input; Carbon-Adjusted Gating Threshold (CAGT), representing conversion of cost and carbon intensity of electricity to a comparable signal; and Adaptive Injection Efficiency Score (AIES), i.e. integration of the former two criteria to guide decisions on whether to inject, defer, or skip the injection, e.g. based on evidence of simpler algorithms with equal or better performance than complex models. Our research and development proceeds in three stages: injection value characterization under different input conditions in application-oriented case studies; designing and evaluating AIES as a gating mechanism for injection against always-on and knowledge-free alternatives; and formalization of AIES as domain agnostic rule-based design useful to relevant applications such as forecasting renewable energy. This work benefits from our experience with sustainable AI, adaptive thresholding and decomposition-based forecast modelling. Due to addressing environmental issues in addition to accuracy and domain knowledge, this work can contribute positively to the societal angles of sustainable AI. By aiming to reduce carbon emissions without compromising on performance, it has health, social and humanities benefits as broader impacts.